The TRIP PI's at the National Center for Atmospheric Research (NCAR), Chin-Hoh Moeng and Peter Bogenschutz, have primarily focused their time on the implementation of the Simplified-Higher Order Turbulence Closure (SHOC; Bogenschutz and Krueger 2013) to the multi-scale modeling framework (MMF) and testing of SHOC on deep convective cloud regimes.

1) Implementation of SHOC into MMF

Through funding of this project we have successfully implemented the SHOC scheme into the Colorado State University (CSU) MMF. The CSU MMF represents a coupling between NCAR's Community Atmosphere Model (CAM) and the System for Atmosphere Modeling (SAM; Khairoutdinov and Randall 2003) cloud resolving model (CRM). Thus, the CSU MMF is known as the "superparameterized" CAM (SP-CAM; Khairoutdinov et al. 2005). Here we implemented SHOC into SAM, to replace the simple 1.5 TKE closure with an assumed-PDF based parameterization.

SP-CAM-SHOC has been successfully run for multi-year climate simulations for two configurations; one with the default single-moment microphysics scheme and one using the Pacific Northwest National Laboratory (PNNL) configuration, which uses a double moment microphysics scheme and sophisticated aerosol treatment. In both configurations, SP-CAM-SHOC improves the fidelity of the simulations compared to the default SP-CAM.

Figure 1 displays the shortwave cloud forcing biases, computed relative to CERES-EBAF, for SP-CAM (left column) and SP-CAM-SHOC (right column) run with both the simple microphysics (middle row) and the PNNL configuration (bottom row). Cool colors indicate regions where the simulated clouds are too reflective and warm colors indicated regions where the simulated clouds are not reflective enough. It is clear that for both the single and double microphysics cases that SP-CAM-SHOC improves the overall RMSE score, compared to the standard SP-CAM. However, more importantly, SP-CAM-SHOC ameliorates several regional biases present in SP-CAM.

Since the embedded cloud resolving model in SP-CAM has a horizontal grid size of 4 km, low-level boundary layer clouds, such as stratocumulus (Sc) and cumulus (Cu) are not resolved. In addition, the simple 1.5 TKE closure and "all or nothing" condensation scheme in SP-CAM are inadequate to properly parameterize these types of clouds. This is evident in Figure 1 for SP-CAM simulations, which generally shows a lack of Sc clouds off the western coasts of the continents (more specifically, the Peruvian and Californian Sc regions). SP-CAM-SHOC, with its better treatment of SGS turbulence and clouds, greatly improves the representation of maritime Sc clouds.

In addition, the improved representation of maritime Sc in SP-CAM-SHOC is not at the expense of the simulated climate. As demonstrated in Figure 1, improvements in the simulated shortwave cloud forcing can also be seen in the tropics. This is related to improved representation of SGS mixing in SHOC, which prevents deep convection from being too intense (Varble et al. 2011). While not shown, SP-CAM-SHOC also marginally improves other aspects of the climate simulation such as precipitation and surface temperature. The overall "Talyor score", a metric that gives the quality of a climate simulation in one objective number, is better for SP-CAM-SHOC than SP-CAM. Results of these climate simulations are forthcoming in a peer-reviewed paper to be submitted soon.

1a) Aerosol-Cloud Interaction Experiments with SP-CAM-SHOC

It is widely agreed that most conventionally parameterized GCMs overestimate the positive relationship between aerosol optical depth and liquid water path (Quass et al. 2009), resulting in large changes in the cloud radiative effects. This can result in an unrealistic simulation of the 20^{th} century, as well as misleading climate change simulations. Wang et al. (2011) showed that the PNNL SP-CAM greatly reduces the indirect effects due to aerosols, compared to conventional GCMs, because precipitation processes were shifted primarily from autoconversion to accretion, due to a prognostic precipitation scheme. However, the PNNL SP-CAM does not realistically simulate low-level clouds, in which aerosol effects can be potentially very climatically important.

We ran the PNNL SP-CAM with SHOC with present day and pre-industrial aerosol emissions to asses the aerosol-cloud interactions when low level clouds and turbulence are better represented. Simulations are five years in length. Table 1 presents the changes in top of atmosphere flux perturbations, the aerosol-cloud radiative effects, and the changes in liquid water path. Overall, SP-CAM-SHOC exhibits a slightly lower sensitivity to aerosols when compared to SP-CAM and a version of CAM5 that employees a prognostic precipitation scheme. The values SP-CAM-SHOC produces are well within the range of observational uncertainty (Quass et al. 2009).

1b) Coupled Experiments with SP-CAM SHOC

We recognize the importance of running coupled experiments with proposed parameterizations to detect any unwanted feedbacks that may inadvertently develop from improving a physical process. Thus, we ran the versions of SP-CAM and SP-CAM-SHOC with the simple single-moment microphysics scheme for 10 years in a pre-industrial control run configuration. Neither SP-CAM simulation was tuned to achieve a pre-industrial top of atmosphere radiation balance of ~0 W/m2, thus after 10 years of integration SP-CAM had an imbalance of 1.9 W/m2 while SP-CAM-SHOC had an imbalance of -1.4 W/m2.

Therefore, the simulations were stopped after 10 years as the climate would inevitiably drift with a longer integration. While both SP-CAM and SP-CAM-SHOC would need to be tuned before science could be performed in a coupled climate simulation, it is encouraging to note that there were no "surprises" from the SP-

CAM-SHOC coupled simulation and that the improvements seen in the prescribed SST simulations (i.e. improved Sc) were also present in the coupled simulation. Therefore, we have high confidence that a tuned version of SP-CAM-SHOC will produce a successful climate simulation. Future work will focus on tuning the coupled simulation.

2) Testing SHOC on Deep Convective Regimes

In addition to testing SHOC in the SP-CAM framework we simulated deep convective cases in the context of the standalone cloud resolving model, SAM. Here we used the ARM Tropical Warm Pool International Cloud Experiment (TWP-ICE) case. Bogenschutz and Krueger (2013) had previously found that SAM-SHOC was less sensitive to changes in horizontal and vertical resolution for boundary layer clouds than the standard SAM with it's 1.5 TKE closure (hereafter referred to as SAM-TKE). Here we wish to examine the sensitivity of SAM-SHOC to changes in horizontal resolution for a deep convective case.

The ARM TWP-ICE case was simulated and compared between 1) LES using 2048 x 2048 x 256 grid points with a horizontal grid mesh of 100 m (often referred to as a GigaLES, performed at CSU by Don Dazlich and David Randall) and 2) SAM-TKE and SAM-SHOC with horizontal grid sizes of 0.8, 1.6, 3.2, and 6.4 km to test the scale sensitivity.

Figure 2 displays the temporally and spatially averaged profiles of total cloud condensate, total heat flux, and SGS heat flux from TWP-ICE simulations from day 19.75 to 20.5 (an active period) for both SAM-TKE and SAM-SHOC for grid sizes ranging from dx = dy = 0.8 km to 6.4 km. For the base case of dx = dy = 1.6 km, both SAM-TKE and SAM-SHOC show realistic simulation of deep convection with a distinct tri-modal distribution of clouds. Although not shown, an examination of the time evolution of the horizontally averaged cloud water and ice shows very similar and realistic behavior between these two configurations when dx = dy = 1.6 km. However, we wish to examine how robust the simulations are to changes in resolution.

Total condensate profiles shows an obvious sensitivity for SAM-TKE in simulating low-level clouds, while SAM-SHOC is much more robust. This result is not so surprising as SHOC was originally designed to treat unresolved low-level boundary layer clouds. However, it is also evident that SAM-SHOC shows sensitivity to the grid size for high-level clouds. The reason for this is currently not known but is being investigated. We are examining the coupling of SHOC with the ice microphysics as a potential culprit.

An explanation of the sensitivities seen in the low-level clouds for SAM-TKE can be achieved by looking at the profiles for the heat flux. The horizontally and temporally averaged total heat flux profiles differ by 100 W/m2 between the SAM-TKE simulations at the coarsest and finest resolution. While SAM-SHOC also shows some sensitivity for the total heat flux, the differences are much smaller than those of SAM-TKE. A clearer picture emerges when only the SGS contribution is analyzed.

We would expect that as grid size increases, the simulated SGS contribution would increase, while the total heat flux remains the same. However, SAM-TKE has a negligible contribution to the SGS heat flux for all grid resolutions, suggesting an unrealistic partitioning between SGS and resolved heat flux. SAM-SHOC, however, does increase the SGS contribution as grid size increases. While this realistic partitioning behavior is encouraging, it should be noted that when a filter is applied to the GigaLES to determine the magnitude of the SGS heat flux for a particular grid size, it is obvious that SAM-SHOC is still underestimating the SGS turbulence for all grid sizes. Thus, future work will focus on improving SAM-SHOC's representation of SGS turbulence and heat fluxes for deep convection, for a more scale insensitive simulation.

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Simulation	ΔR (W/m2)	ΔCRE (W/m2	ΔSWCF (W/m2)	ΔLWCF (W/m2)	ΔLWP (%)
SP-CAM **(Wang et al. 2011)**	-1.05	-0.83	-0.77	-0.06	+3.9%
SP-CAM-SHOC	-0.98	-0.62	-0.63	+0.01	+2.8%
CAM5-MG1 **(diagnostic precipitation)**	-1.50	-1.42	-1.79	+0.37	+8.9%
CAM5-MG2 **(prognostic precipitation)**	-1.08	-0.76	-0.91	+0.15	+5.8%

Table 1. Radiative flux perturbation from various simulations (all are five year simulations at 2-degree horizontal resolution). Differences shown are for simulation with 1850 and 2000 aerosol emissions. R = top of atmosphere flux, CRE = total cloud radiative forcing, SWCF = shortwave cloud forcing, LWCF = longwave cloud forcing, LWP = liquid water path.

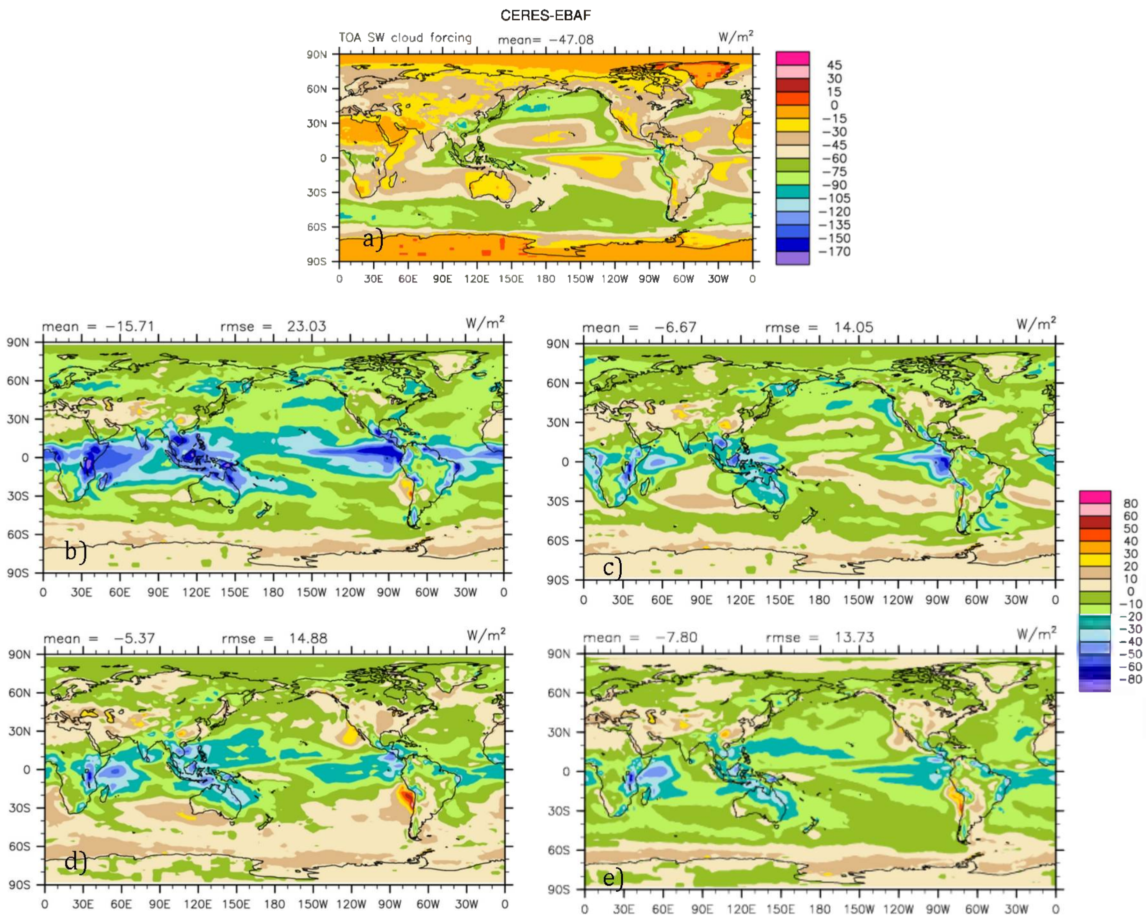

Figure 1. Shortwave cloud forcing from a) CERES-EBAF observations (top) and the shortwave cloud forcing biases computed relative to CERES-EBAF for b) SP-CAM, c) SP-CAM-SHOC, d) PNNL-SP-CAM, and e) PNNL-SP-CAM-SHOC.

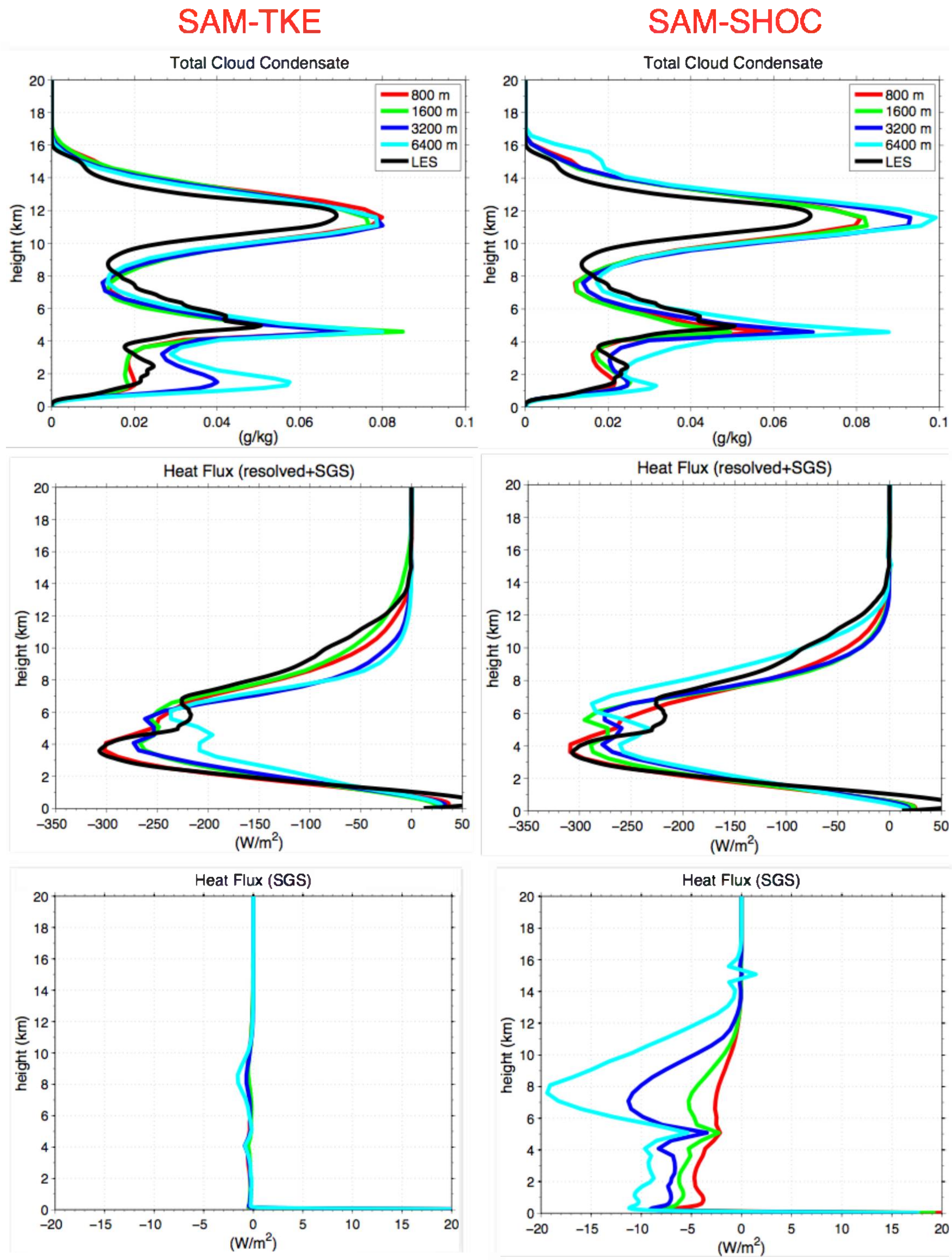

Figure 3. Temporally and spatially averaged profiles from TWP-ICE simulations from day 19.75 to 20.5 (active period) for (left) SAM-TKE and (right) SAM-SHOC for various horizontal grid sizes. The black curve represents the GigaLES.